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14. ABSTRACT

This contract has resulted in three major research accomplishments: (1) epitaxial growth of GaAsN and InGaAsN with excellent optical properties, (2) detailed understanding of kinetics of the nitrogen incorporationi in (In)GaAsN, and (3) growth of high quality GaN, AlN and AlGaN, over the entire range of compositions, by gas source molecular beam epitaxy. These three areas are discussed in the report.

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"GaInAsN/InP Lasers with Low Linewidth Enhancement Factor"

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RESEARCH ACCOMPLISHMENTS:

This contract has resulted in three major research accomplishments: (1) epitaxial growth of GaAsN and InGaAsN with excellent optical properties, (2) detailed understanding of kinetics of the nitrogen incorporation in (In)GaAsN, and (3) growth of high quality GaN, AlN, and AlGaN, over the entire range of compositions, by gas source molecular beam epitaxy. These three areas are discussed in this report. Published papers documenting our results are enclosed.

RESEARCH RESULTS

(1) Epitaxial growth of GaAsN and InGaAsN.

We have established high quality growth of GaAsN and InGaAsN using active nitrogen derived from dimethylhydrazine (DMHY). DMHY is a convenient source of active nitrogen since it decomposes at a low temperature of about 130°C, at the growing surface. This allows for the growth of GaAsN and InGaAsN with the N fraction close to ~1% and good optical properties. This N content is sufficient to allow for the preparation of lasers based on active layer structures with a single quantum well of InGaAsN operating at 1.3 micron. However, DMHY is very reactive and it forms adducts with metalorganic sources of Ga, thus greatly complicating growth kinetics.

The ability to grow nitrides of GaAs with excellent optical properties allowed us to establish a fairly comprehensive data set for the bandgap dependence of GaAsN with the increasing incorporation of nitrogen. This is shown in an enclosed figure listing our own results and results of other groups. The data is in good agreement with the model proposed long ago by Van Vechten. The more recent models, refinements of the old model, do not seem to work equally well.

In order to produce InGaAsN structures emitting close to 1.30 μm, we introduced as much In as possible (about 0.36), without going over the critical strain, and then added nitrogen. This assumed that the incorporation of In would be relatively easy and that In would be more effective in reducing the bandgap than the N. The problem is that the incorporation of In and N compete. Once In is introduced, the amount of N that can be incorporated into the alloy drops down to less than ~1%. It is then very difficult to get longer wavelength luminescence.

(2) *Kinetics of nitrogen incorporation in (In)GaAsN*

Complexities of crystal growth of GaAsN and InGaAsN have been mapped out through a set of growth experiments. We have been able to formulate a model of growth that accurately accounts for all major dependencies encountered in epitaxy of nitrides of GaAs. Nitrogen incorporation into the solid was investigated as a function of the substrate temperature and fluxes.

The nitrogen incorporation kinetics and growth mechanism have been modeled by assuming formation of an adduct arising from reactions between triethylgallium and dimethylhydrazine, while neglecting reactions between precursors of trimethylindium and dimethylhydrazine. The model accounts for experimentally observed relationship between growth rates and nitrogen incorporation in GaAsN and InGaAsN. Our experiments show that the absolute arsenic flux and the As/N flux ratio play a critical role in the growth of single phase GaAsN. dependence on the temperature and fluxes. This first version of the model is described in the enclosed paper entitled "Metalorganic molecular beam epitaxy of GaAsN with dimethylhydrazine ". The paper was published in Applied Physics Letters. A publication describing a more complete model has been submitted to the Journal of Applied Physics.

3) Growth of high quality GaN, AlN, and AlGaN

Gas source molecular beam epitaxy with ammonia was used to grow GaN, AlN, and $Al_xGa_{1-x}N$ on Si(111). The transition between the (7 x 7) and (1 x 1) silicon surface reconstructions, at 1100K, was used for *in-situ* calibration of the substrate temperature. In all cases, the initial deposition of Al, at 1130-1190K, produced an effective nucleation layer for the growth of AlN. The Al layer also reduced islands of SiN_x that might be formed due to background NH_3 on the silicon surface prior to the onset of epitaxial growth. The transition to two-dimensional layer-by-layer growth mode, under optimum conditions, was obtained after the initial AlN thickness of ~7 nm. Rapid transition between the 3D and 2D growth modes is essential for control of interfacial strain and the subsequent cracking of the epitaxial layer.

In the growth of $Al_xGa_{1-x}N$ we experimented with three types of buffer layers, containing AlN, AlGaN/AlN and AlGaN/GaN. Short period superlattices were used and their effectiveness evaluated by x-ray diffraction. We determined that a combination of AlN buffer layer, prepared under the two-dimensional growth mode, with a short period superlattice of AlGaN/GaN results in the highest quality AlGaN. Under optimized growth conditions, x-ray diffraction coherence length almost equal to the layer thickness was obtained for low Al content layers. The normalized coherence length was reduced to ~0.4

for x=0.66 and it increased again to ~0.75 in AlN. From room temperature bandedge cathodoluminescence of AlGaN grown on Si(111) we determined the alloy bowing coefficient of b=1.5 eV, in good agreement with previous results obtained by absorption measurements. The room temperature cathodoluminescence data obtained on our $Al_xGa_{1-x}N$ is shown in Fig. 2 of this report.

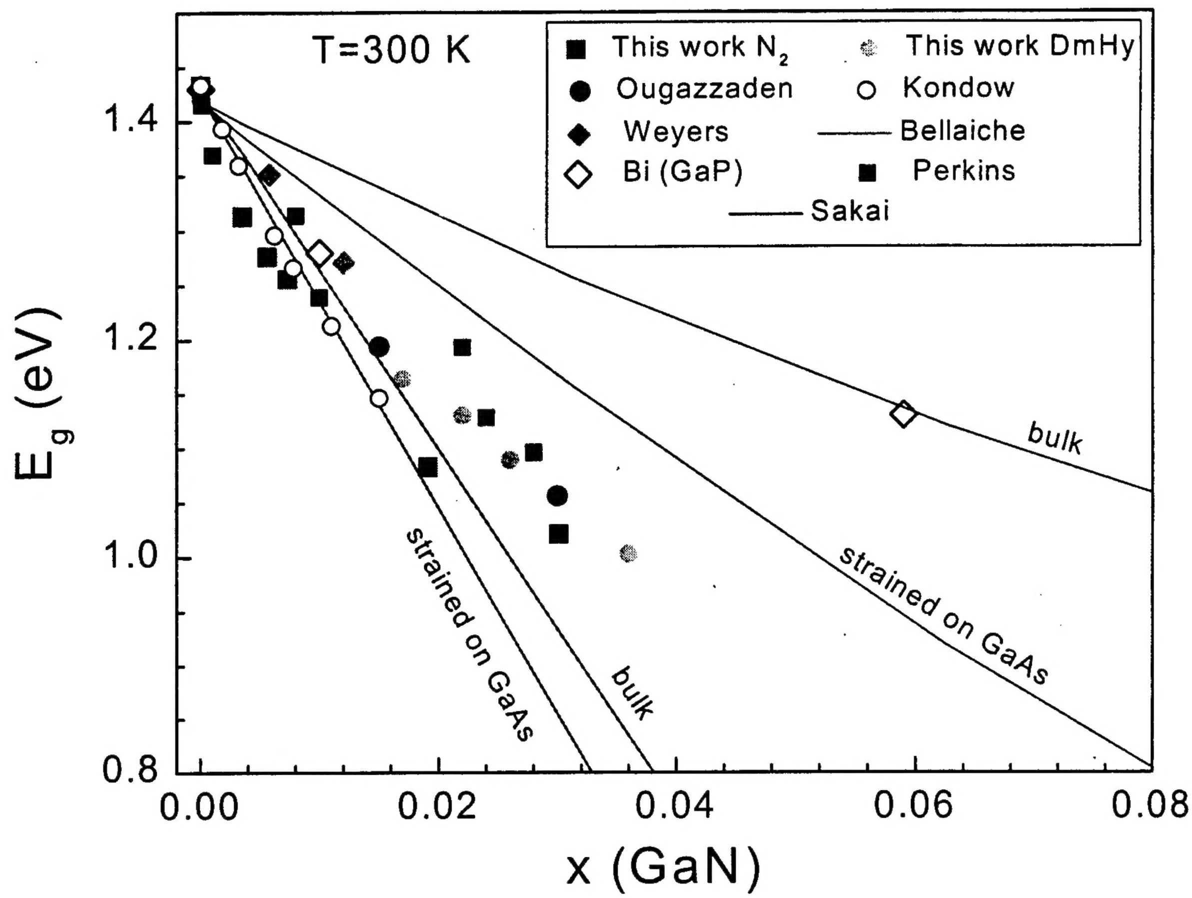

Figure 1 Bandgap of GaAsN with increasing nitrogen content

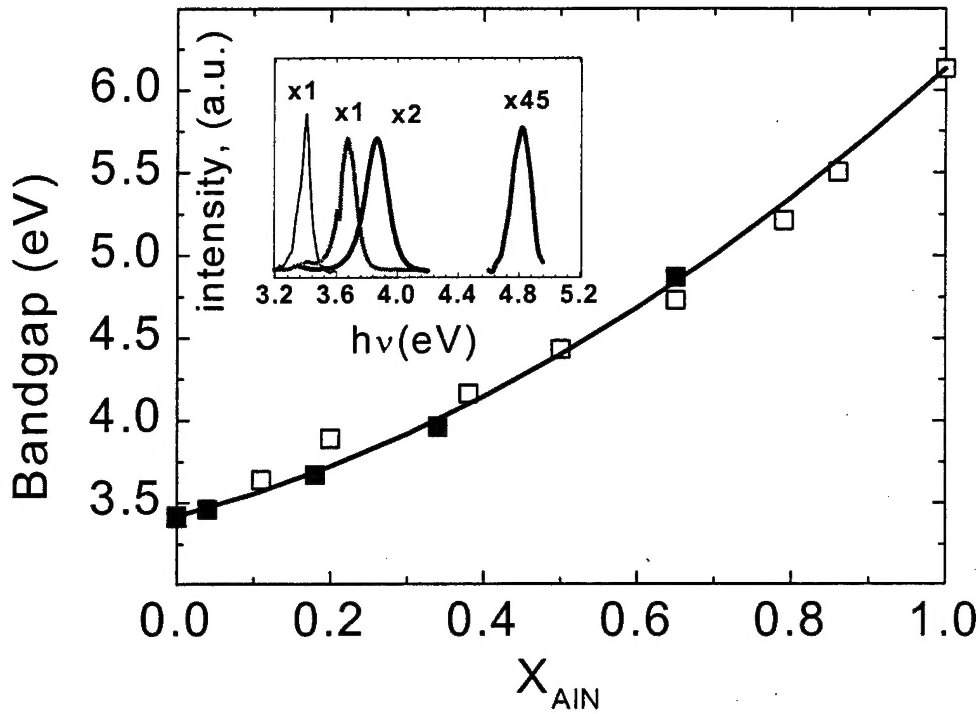

Figure 2 Bandgap of AlGaN with different nitrogen concentrations. Inset shows room temperature cathodoluminescence spectra of selected compositions of AlGaN.

Publications under AFOSR grant "GaInAsN/InP Lasers with low linewidth enhancement factor"

1) "Luminescence of as-grown and thermally annealed GaAsN/GaAs", by S. Francoeur, G. Sivaraman, Y. Qiu, S. Nikishin, and H. Temkin, Applied Physics Letters 72(15), 1857 (1998)

2) "Metalorganic molecular beam epitaxy of GaAsN with dimethylhydrazine", by Y. Qiu, C. Jin, S. Francoeur, S. A. Nikishin, and H. Temkin, Applied Physics Letters 72(16), 1999 (1998)

3) "Raman Studies of Nitrogen Incorporation in $GaAs_{1-x}N_x$", by T. Prokofyeva, T. Sauncy, M. Holtz, Y. Qiu, S. Nikishin, and H. Temkin, Applied Physics Letters 73(10), 1409 (1998)

4) "Nitrogen Incorporation Kinetics in Metalorganic Molecular Beam Epitaxy of GaAsN", C. Jin, Y. Qiu, S. A. Nikishin, and H. Temkin, Applied Physics Letters 74(23), 3516 (1999)

5) "High-quality AlN grown on Si(111) by gas source molecular beam epitaxy with ammonia", S. A. Nikishin, V. G. Antipov, S. Francoeur, N. N. Faleev, G. A. Seryogin, V. A. Elyukhin, H. Temkin, T. I Prokofyeva, M. Holtz, A. Konkar, and S. Zollner, Applied Physics Letters 75(4), 484 (1999)

6) "High quality GaN grown on Si (111) by gas source molecular beam epitaxy with ammonia", S. A. Nikishin, N. N. Faleev, V. G. Antipov, S. Francoeur, L. Grave De Peralta, G. A. Seryogin, H. Temkin, T. I Prokofyeva, M. Holtz, and S. N. G. Chu, Applied Physics Letters 75(14), 2073 (1999)

7) "Excitons Bound To Nitrogen Clusters in GaAsN", S. Francoeur, S. A. Nikishin, C. Jin, Y. Qiu, and H. Temkin, Applied Physics Letters 75(11), 1538 (1999)

8) Nikishin S. A., Faleev N. N., Zubrilov A. S., Antipov V. G., and Temkin H., "AlGaN grown on Si(111) by gas source molecular beam epitaxy", Appl. Phys. Lett., 76, no. 21, 3028-30, (2000).

9) M. Holtz, T. Prokofyeva, M. Seon, J. Vanbuskirk, K. Copeland, S. A. Nikishin, N. N. Faleev, H. Temkin, S. Zollner and A. Konkar, "Vibrational and optical properties of AlN grown on Si(111) using gas-source molecular beam epitaxy", 27th International Conference on Compound Semiconductors, Monterey, CA, October 2-5, 2000.

10) M.Seon M., Prokofyeva T., Holtz M., Nikishin S. A., Faleev N. N., Temkin H., "Selective growth of high quality GaN on Si(111) substrates", Appl.Phys.Lett., 76, no.14, 1842-4 (2000).

11) T. Prokofyeva, M. Seon, J. Vanbuskirk, M. Holtz, S. A. Nikishin, N. N. Faleev, H. Temkin, and S. Zollner, "Vibrational Properties of AlN Grown on Silicon (111)", submitted to Phys. Rev. B. (August, 2000).

12) "Metalorganic molecular beam epitaxy of (In)GaAsN with dimethylhydrazine", C. Jin, S. A. Nikishin, V. I. Kuchinskii, H. Temkin, and M. Holtz, Journal of Applied Physics, submitted for publication